ADVANCED PROPULSION CONCEPTS AT THE JET PROPULSION LABORATORY

Stephanie D. Leifer, Robert H. Frisbee, and John R. Brophy
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Abstract

Current interest in advanced propulsion within NASA and research activities in advanced propulsion concepts at the Jet Propulsion Laboratory are reviewed. The concepts, which include high power plasma thrusters such as lithium-fueled Lorentz-Force-Accelerators, MEMS-scale propulsion systems, in-situ propellant utilization techniques, fusion propulsion systems and methods of using antimatter, offer the potential for either significantly enhancing space transportation capability as compared with that of traditional chemical propulsion, or enabling ambitious new missions.

In addition to potentially addressing the propulsion needs of missions like those of the Human Exploration and Development of Space (HEDS) initiative, outer planet sample returns and orbiters, or an interstellar precursor mission, this research is aiding in fundamental scientific discoveries and developments in other technologies.

Introduction

The Advanced Propulsion Technology (APT) group at the Jet Propulsion Laboratory was established in 1981 to identify and generate advanced propulsion concepts which offer theoretical performance significantly superior to that of state-of-the-art propulsion systems, and to evaluate the feasibility of these concepts through experiment and analysis. Support for this research has been provided by NASA independent of specific flight projects. In the last year, this activity has become part of the Propulsion Research program of the Advanced Space Transportation Program (ASTP) executed by the Marshall Space Flight Center.

The Advanced Propulsion Concepts activity at JPL is sustained with a very modest investment by NASA of about one million dollars per year, yet can have an enormous impact on a variety of NASA programs, basic scientific research, and spin-off technologies. There are many examples of the impact advanced propulsion research has had on the aerospace community. Electric propulsion, considered an advanced technology when the Advanced Propulsion Concepts activity began, is now enabling missions of the New Millennium program. The first of these, Deep Space 1 (DS 1) [1], is scheduled for launch in July of 1998. The DS 1 spacecraft will flyby the near-Earth asteroid McAuliffe at just 5 to 10 kilometers above the surface, then pass by Mars for a gravity assist to enable an encounter with comet West-Kohoutek-Ikemura.

Other examples of the impact advanced propulsion research has had include the fundamental understanding of plasma interactions with magnetic fields that has resulted from modeling work performed on fusion and electron-cyclotron-resonance thruster concepts. New insights into physical and chemical properties of fullerenes, which were considered as a possible ion engine propellant, have been gained. A previous research effort of the Advanced Propulsion Concepts activity at Brown University to design and build a magnetic levitation trap for liquid hydrogen was successfully completed. This work was a necessary precursor to the storage of antihydrogen, which may ultimately be achieved through present efforts in antimatter research. Research performed under this activity in high energy density materials (HEDM) for propulsion, specifically atomic hydrogen and metastable helium, led to the establishment of the Air Force Phillips Laboratory HEDM program. Research at the University of Arizona on the *use* of zirconia cells for $C0_2$ separation on Mars was precipitated by advanced propulsion research in in-situ propellant utilization. This technology is now one of the options available for both the 2001 and 2005 Mars flights.

In what follows, present interest in and opportunities for advanced propulsion research within NASA are described. The research activities in advanced propulsion concepts presently underway at JPL are then presented.

Advanced Propulsion Research

Present Interest in Advanced Propulsion within NASA

In July of 1997, NASA Administrator Daniel S. Goldin announced his interest in an interstellar precursor mission - a mission to 10,000 AU in 50 years. Mr. Goldin has charged the Jet Propulsion Laboratory with investigating the possibilities for such a mission. Subsequent to his announcement, Mr. Goldin visited JPL on July 26, 1997 and was presented with some preliminary material outlining the technology needs and mission considerations for mounting the first interstellar precursor mission. Prominent among the identified needs was advanced propulsion.

An interstellar precursor mission is the most recent and the most ambitious mission goal that could be enabled by the development of advanced propulsion systems. A high energy density concept, such as that which relies on antimatter initiated fusion reactions [2], would be required. Other mission goals, such as multi-body sample-return missions, may be enabled by advanced solar sails with aerial densities between 1 and 5 g/m^2 [3]. Such sails would effectively be able to "turn off" solar gravity. Megawatt-level plasma thrusters could support piloted Mars missions as part of the NASA Human Exploration and Development of Space (HEDS) initiative. Possibilities for the use of electrodynamics tethers on the International Space Station for orbit raising maneuvers or even Earth return of small packages were recently presented at the Tether Technology Interchange Meeting in Huntsville, Alabama [4].

Pursuing the research that will result in the development of advanced propulsion systems is a great challenge at present. Regardless of stated objectives, NASA is not investing heavily in Advanced Propulsion Concepts. The entire Advanced Space Transportation Program with the exception of the Bantam Lifter activity, an effort to develop a small launch system capable of orbiting 100 kg payloads at a targeted cost of $1,000,000 per launch, remains unfunded in both 1998 and 1999.

The Current Research Program

The 1997 research activities at JPL are described below. Additional details can be found in Reference [5].

1. In-Situ Propellant Utilization

Reducing the initial mass in low-Earth-Orbit (IMLEO) of a spacecraft can enable a variety of robotic and piloted missions by dramatically reducing launch costs. One way to lower the IMLEO is to obtain some of the propellant required for the mission from extraterrestrial resources, many of which could provide oxygen.

The principle barrier to the use of oxygen as propellant in plasma thrusters is the development of a cathode which can tolerate the oxygen environment. Field emitter cathodes are efficient, low-power, and easily scaleable and have the potential to be functional in an oxygen environment. The successful demonstration of a cathode that operates on oxygen would enable In Situ Propellant Utilization (ISPU) for a variety of advanced propulsion concepts, including trans-lunar cargo propulsion systems.

In a collaborative effort with the University of Michigan, BMDO, and the Linfield Research Institute, hafnium carbide field-emitter arrays are being evaluated for operation in oxygen. These field emitter arrays have demonstrated low turn-on voltages, high current densities, and stable operation in a pulsed mode.

2. High Power Lorentz-Force Accelerator

The purpose of this activity is to investigate the feasibility of megawatt-class, Lorentz-Force Accelerator (LFA) thrusters utilizing metal propellants such as Lithium or Lithium/Barium. Among all candidate plasma propulsion options, the lithium-fed LFA has the unique potential to produce high thrust densities (10^2 to 10^5 N/m^2) while processing very high power (10^5 to 10^7 W) through a compact, simple device at a high specific impulse (4000-6000 s). These characteristics put the LFA thruster in a class by itself for application to many thrust-intensive and energetic missions [6-7] such as those being examined for the Human Development and Exploration of Space initiative. Furthermore, it may be well suited for fast robotic missions to the outer solar system. This activity is a collaboration between JPL, Princeton University, and the Moscow Aviation Institute (MAI).

Current LFA thruster research at JPL is centered on evaluating the feasibility of obtaining sufficient component lifetime. Earlier this year at MAI, a Li-LFA system was tested at 122 kWe, demonstrating 44% efficiency at 3500 s. The wear rate on this cathode was consistent with a component lifetime of up to 1000 hours.

3. Micropropulsion

The recent interest in developing microspacecraft in the 1-20 kg class necessitates the development of advanced, lightweight, small volume propulsion systems. For primary propulsion of interplanetary spacecraft, these micro-propulsion systems will have to provide large specific impulses to reduce propellant mass. Attitude control requirements are nearly as difficult as primary propulsion for microspacecraft as well.

Using microfabrication techniques, we are investigating the feasibility of achieving order-of-magnitude mass and volume reductions over state-of-the-art propulsion systems while taking into account special MEMS design requirements (i.e. temperature, pressure, and material constraints).

It is important to note that MEMS-scale propulsion systems and components may have applications for systems other than microspacecraft; there may be benefits of redundancy, reliability, and scalability by using arrays of micromachined components.

4. Antimatter

Matter-antimatter annihilation offers the highest energy density of any known reaction substances, making the use of antimatter very attractive for propulsively ambitious space missions. Methods of using small amounts of antimatter to initiate fission and fusion reactions are currently being studied. Two such concepts have been proposed by Dr. Gerald Smith of the Pennsylvania State University. The first of these concepts is the Ion Compressed Antimatter Nuclear, or ICAN [2] method. ICAN is an inertial confinement fusion concept, requiring high intensity laser or ion beams to compress a target composed of uranium, tritium, and deuterium, which is then bombarded by antiprotons. The antiprotons annihilate with nucleons in the fissionable target atoms, The energy released is sufficient to facilitate the initiation of a fusion burn. The present conception of how to couple the energy released in the antiproton initiated fission/fusion reaction is by a technique somewhat analogous to the ORION concept [8]. Specifically, ICAN would operate by a series of explosions which heat and ablate a pusher-plate; the resulting expanding plasma would generate thrust [9]. Systems and mission studies of an ICAN propulsion system indicate the potential for fast piloted Mars missions (120 day round-trip, inclusive of a 30 stay), a 3-year fast Pluto flyby, and a 1.5 year piloted Jupiter mission.

More recently, the concept of Antiproton Initiated Microfusion (AIM) in electromagnetic traps was introduced [10]. There are two very significant benefits of AIM should it prove feasible. First, it would not require fuel pellet compression, which would enormously reduce the mass and complexity of a propulsion system based on this technology. The second benefit is that the daughter products resulting from antiproton induced fission of U^{238} have very little residual radioactivity as compared with those which result from conventional thermal neutron-induced fission of U^{235} [11]. This may have significant consequences for the feasibility of developing clean nuclear propulsion systems.

Over the past several years, NASA's Advanced Propulsion Concepts program has supported researchers at Penn State to experimentally investigate antimatter trapping, storage, and manipulation for applications to space propulsion. Part of this work has been the development of the world's first portable Penning trap for the storage and transport of antiprotons. Most recently, the Penn State team was successful in the capture and storage of 10 million antiprotons in ten successive pulses from the Low Energy Antiproton Ring (LEAR) at CERN.

5. Fusion

While the ICAN concept relies on the novel use of antiprotons, it is, fundamentally, a fusion propulsion concept. Numerous other fusion energy-based propulsion concepts have been proposed, and many are currently under investigation elsewhere [12]. Almost invariably, these concepts can be categorized as inertial- or magnetic- confinement fusion based, and require massive system components [13]. One possible exception to this is the Dense Plasma Focus (DPF).

The DPF is a table-top device presently being examined under the advanced propulsion concepts activity. Lawrenceville Plasma Physics, in cooperation with Centrus Plasma Technologies, is performing DPF simulations and experiments. The goal of this research is to assess the feasibility of a fusion propulsion system based on the use the pulsed magnetic pinch effect, A DPF propulsion system would operate at very high specific impulse, yet at a thrust-to-weight ratio that is orders-of-magnitude below those of other fusion systems. This device may be capable of operating on a number of fusion fuels including p-B^{11}. However, unlike most inertial-or magnetic-confinement fusion systems, it is not necessary that it operate at a high gain. In fact, the gain of the DPF thruster is estimated to be around one, corresponding to scientific break-even.

Because of its small size and relatively simple design, the DPF device represents a departure from other fusion systems, as it permits fundamental fusion research at very low cost.

6. Advanced Propulsion Concepts Mission and Systems Evaluation

Most advanced propulsion concepts research activities have as their objectives to understand the underlying physics and to evaluate the feasibility of an advanced propulsion device. One cost effective-method for circumventing the difficulties encountered in laboratory testing of some advanced concepts is to conduct virtual experiments; we are developing a first-principals-based, high-performance virtual simulation capability on massively parallel supercomputers for the evaluation of advanced propulsion concepts.

A recent example of the application of this capability is an analysis of the Magnetic Sail concept proposed by Zubrin [14]. The concept is for a magnetic field generated by a superconducting loop to deflect plasma wind, thereby creating thrust. Single particle models (in configurations of both axially and normally directed charged particles) were used to predict performance. For comparison with prior estimates, we modified a 3-D particle-in-cell (PIC) code to develop a 3-D single particle model. The thrust predicted by these simulations was an order-of-magnitude lower than that estimated previously [14].

Mission evaluation performed from a complete systems perspective is another crucial element of the advanced propulsion concepts program; it provides quantification of potential mission benefits of an advanced concept, Because the various performance characteristics of a technology (e.g. specific impulse, efficiency, and specific mass) can be treated parametrically in an analysis, this capability is used to identify the system parameters that are the primary performance drivers for a mission and conversely, to identify those that have little impact on performance. This technique aids in rapid identification of concepts that yield no significant performance enhancements so that they need not be pursued further.

Summary

An interstellar precursor mission, as well as other goals in deep space exploration such as those of the Human Exploration and Development of Space (HEDS) initiative, will require advanced propulsion technology to be realized. Concepts currently under study through the JPL Advanced Propulsion Concepts activity, which include high power plasma thrusters such as lithium-fueled Lorentz-Force-Accelerators, MEMS-scale propulsion systems, in-situ propellant utilization techniques, fusion propulsion systems and methods of using antimatter, may lead to the technology necessary to accomplish these ambitious missions. Mission and systems evaluation performed under this activity provides quantification of the potential benefits a new advanced concepts may hold for these ambitious missions as well.

Acknowledgments

The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

1. http: //nmp.jpl.nasa.gov/ds I/Mission/
2. Lewis, R. A., Newton, R., Smith, G. A., and Toothacker, W.S, “An Antiproton Catalyst for Inertial Confinement Fusion Propulsion, “ AIAA 90-2760, AIAA/SAE/ ASME/ASEE 26th Joint Propulsion Conference, Orlando, FL, July 16-18, 1990.
3. Proceedings of the NASA-JPL Workshop on Solar Sail Propulsion, Jet Propulsion Laboratory, Pasadena, CA, February 13, 1997.
4. Proceedings of the Marshall Space Flight Center Tether Technology Interchange Meeting, Huntsville, Alabama, September 9th and 10th, 1997 (in progress).
5. Leifer, S. D., Frisbee, R. H., Brophy, J. R., “The NASA Advanced Propulsion Concepts Program at the Jet Propulsion Laboratory,” AIAA 97-2792, AIAA/ASME/SAE/ASEE 33rd Joint Propulsion Conference, Seattle WA, July 6-9, 1997.
6. Goodfellow, K., Polk, J., “Lorentz Force Accelerator Technology Development at JPL,” Proceedings of the Sixth Advanced Space Propulsion Workshop, pp. 129-136, NASA-JPL, Pasadena, CA 1995,
7. Choueri, E., Chiravalle, V., Miller, G. E., Jahn, R. G., “Lorentz Force Accelerator with an Open-ended Lithium Heat Pipe,” AIAA-96-2737, 32nd AIAA Joint Propulsion Conference, Lake Buena Vista, FL, July 1-3, 1996.
8. Martin, A. R., Bond A., “Nuclear Pulse Propulsion: A Historical Review of an Advanced Propulsion Concept,” J. Brit. Int. Sot., 32, pp. 283-310, 1979.
9. Smith, G. A., “Antimatter: Applications to Propulsion,” Eighth Annual Symposium on Space Propulsion, Pennsylvania State University, Ott 30-31, 1996.
10. Smith, G. A., “Antimatter-Initiated Microfusion (AIM) in Electromagnetic Traps,” Proposal to the Department of Energy, Office of Energy Research, Notice 97-08, May 8, 1997.
11. Smith, G. A., “Antiproton-Catal yzed Microfission/Fusion Propulsion Systems,” NASA-JPL Eighth Advanced Space Propulsion Research Workshop, Pasadena, CA, May 20-221997.

12. Proceedings of the Fusion Propulsion Workshop Technical Interchange Meeting, NASA Marshall Space Flight Center, Huntsville, AL, March 25-26, 1997.
13. Sargent, M. G., “A Comparison of Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF) for Spacecraft Propulsion,” JPL D-5878, Pasadena, CA, 1988.
14. Zubrin, R., Andrews, D., “Magnetic Sails and Interplanetary Travel,” J. Spacecraft, 28(2), pp. 197-203, 1991, and Zubrin, R., “The Use of Magnetic Sails to Escape from Low Earth Orbit,”J. Brit. Int. Sot., 46, pp. 3-10, 1993.